The Iron Atom as Mass Unit in Meteorites, Tektites, and Igneous Rocks

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ABSTRACT

It is shown that in most meteorites (and even in tektites and igneous rocks) the weight per cent of iron is close to its cation per cent. For example, the total weight per cent of iron in Holbrook is 21.56; the cation per cent of iron in the same stone, as calculated from the analysis, is 21.26. This relationship means that in any piece of Holbrook containing 21 iron atoms—the iron evenly distributed—each iron atom constitutes 1 per cent of the total weight. But if the 21 iron atoms weigh 21 per cent, all the other atoms (the 79 other cations plus oxygen atoms plus sulphur atoms, and so on) weigh 79 per cent—the same as 79 iron atoms. Therefore this whole piece of Holbrook contains the mass of 100 iron atoms. This stoichiometric relationship could be reached in a closed system by a partial splitting into lighter atoms of material consisting mostly of iron. In the case of Holbrook, 79 per cent of the original matter is split up and 21 per cent remains.

Some 10 years ago I observed that the weight per cent of iron in a chondrite is numerically the same as the atom per cent of iron if the atom per cent of iron is calculated on an (O, S, H, C)-free basis. I also found that, in meteoritic material, the sum of the quotients of the experimentally determined weight percentages and their atomic or molecular weights (the sum of the molecular proportions) is a constant and equals 1.79.

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TABLE 1

EXAMPLES OF SUMS OF MOLECULAR QUOTIENTS IN METEORITES,
TEKTITES, AND IN G-1 AND W-1

		Total Fe in Weight Per Cent	References
METEORITES			
Angra dos Reis Aa	1.77	7.46	Ludwig and Tschermak, 1909
Tatahouine Ah	1.85	12.16	Lacroix, 1932 (Raoult)
Pasamonte Ap	1.73	16.00	Foshag, 1938
Peramiho Ap	1.74	16.04	Berwerth, 1903 (Ludwig)
Nakhla Ad	1.74	16.15	Prior, 1912
Manbhoom Ch	1.81	19.11	Mason and Wiik, 1964
Appley Bridge Ch	1.81	20.08	Mason and Wiik, 1964
Holbrook Ch	1.83	21.56	Mason and Wiik, 1961b
Chateau Renard Ch	1.82	22.20	Mason and Wiik, 1961a
Karoonda Cp	1.79	25.55	Mason and Wiik, 1962
Estacado Cb	1.79	27.88	Mason and Wiik, 1963
Richardton Cb	1.81	29.79	Mason and Wiik, 1963
Atlanta Ce	1.80	28.95	Wiik, unpublished
Rose City Cb	1.79	36.40	Wiik, unpublished
Steinbach S	1.75	53.01	Winkler, 1878
Marjalahti P	1.83	75.80	Borgström, 1903
TEKTITES			
Caramut, Victoria	1.73	3.96	Taylor, 1962
Telangatuk, Victoria	1.73	3.47	Taylor, 1962
Kalgoorlie, Western Australia	1.74	3.99	Taylor, 1962
Charlotte Waters, central Australia	1.71	3.47	Taylor, 1962
IGNEOUS ROCKS			
Granite, Rhode Island (G-1)	1.78	1.42	Fairbairn, 1953
Diabase, Virginia (W-1)	1.79	7.81	Fairbairn, 1953

The 1.79 is the same as 100/Fe and can be directly derived from the first observation. The equation

$$\frac{\text{weight } \% \text{ Fe}}{\text{Fe}} + \frac{\text{weight } \% \text{ Ni}}{\text{Ni}} + \frac{\text{weight } \% \text{ FeS}}{\text{FeS}} + \frac{\text{weight } \% \text{ MgO}}{\text{MgO}} +$$

$$\frac{\text{weight } \% \text{ Al}_2\text{O}_3}{\frac{1}{2}(\text{Al}_2\text{O}_3)} \ldots = \frac{100}{\text{Fe}} = \frac{100}{55.85} = 1.79$$

is a direct consequence of the observation that the cation per cent of iron is equal to the weight per cent of iron in meteoritic matter.

At the time, however, I did not publish this equation expressing the constancy of the sum of molecular proportions in a meteorite analysis, since I believed that the relationship was either a coincidence or depended on stoichiometric requirements. Later I observed that the equation was applicable to tektites and to many plutonic rocks. On the other hand, the equation does not hold for carbonaceous chondrites of types I and II or for the enstatite achondrites. However, there are certain indications that the observations have value. The relationship cannot be purely coincidental because of the large number of meteorites from different groups that fit it. It is also not a question of stoichiometric requirements, as is shown below. Table 1 gives some typical examples of the constancy of the sum of molecular proportions, and table 2 compares the weight percentages and atomic percentages of iron (on a volatile-free basis) in different meteorites and other rocks. Table 2 includes two examples of carbonaceous chondrites of type I and two examples of type II, and one enstatite achondrite. Since my own analyses are almost entirely of chondrites, I have included in these tables analyses of meteorites of other groups selected from the literature. The classification of the meteorites in tables 1 and 2 is that of Mason (1962b).

Table 1 shows that the sum of the molecular proportions for any analysis is always close to 1.79, and from table 2 it can be seen that the weight percentage of iron is remarkably close to the cation percentage of iron. It is noteworthy that the carefully analyzed standard rocks G-1 and W-1 agree perfectly with the iron equation.

These relationships cannot depend on stoichiometric requirements, which can be seen from the following discussion. If the molecular weights were all equal to or near the weight of Fe (55.85), then under all circumstances the sum of the terms in the equation would equal 1.79. However, many of the components have molecular weights quite different from 55.85, hence 100/(molecular weight of component) differs considerably from 1.79. The principal components in meteorites are the following:

	ATOMIC OR MOLECULAR WEIGHT	
Fe	55.85	$100/55.85 = 1.79$
Ni	58.69	$100/58.69 = 1.70$
FeS	87.91	$100/87.91 = 1.14$
FeO	71.85	$100/71.85 = 1.39$
SiO_2	60.06	$100/60.06 = 1.66$
MgO	40.32	$100/40.32 = 2.28$
$\frac{1}{2}(Al_2O_3)$	50.97	$100/50.97 = 1.96$
CaO	56.08	$100/56.08 = 1.78$

TABLE 2

COMPARISONS BETWEEN WEIGHT PER CENT OF IRON AND CATION
PER CENT OF IRON IN METEORITES, TEKTITES, AND G-1 AND W-1

	Weight Per Cent of Fe	Cation Per Cent of Fe	References
METEORITES			
Manbhoom Ch	19.11	18.91	Mason and Wiik, 1964
Chainpur Ch	19.78	19.71	Keil, Mason, Wiik, and Fredriksson, 1964
Appley Bridge Ch	20.08	19.89	Mason and Wiik, 1964
Knyahinya Ch	20.15	19.90	Mason and Wiik, 1963
Vårvik (Näs) Ch	20.18	20.83	Mason and Wiik, 1964
Hökmark Ch	21.00	21.55	Wiik, unpublished
Ottawa Ch	21.24	20.93	Mason and Wiik, 1961a
Holbrook Ch	21.56	21.26	Mason and Wiik, 1961b
New Concord Ch	21.60	21.40	Mason and Wiik, 1961a
Långhalsen Ch	21.76	21.46	Wiik, unpublished
Mocs Ch	21.81	21.45	Mason and Wiik, 1961a
Varpaisjärvi Ch	21.85	21.44	Wahl and Wiik, 1950
McKinney Ch	21.88	21.79	Wiik, 1950
Monte das Fortes Ch	21.04	20.62	Jérémine, 1954
Kyushu Ch	22.02	21.62	Mason and Wiik, 1961b
Chateau Renard Ch	22.20	21.77	Mason and Wiik, 1961a
Linum Ch	22.37	22.23	Wiik, 1956
Mokoia Cp	24.04	24.82	Wiik, 1956
Vigarano Cp	24.71	25.85	Mason, 1963
Grosnaja Cp	24.80	27.92	Mason, 1963
Karoonda Cp	25.55	25.92	Mason and Wiik, 1962
Lancé Cp	25.58	24.82	Wiik, 1956
Ornans Cp	25.83	26.46	Mason, 1963
Felix Cp	25.94	26.17	Wiik, 1956
Warrenton Cp	26.18	25.72	Wahl, 1950a
Selma Cb (weathered)	22.08	24.40	Mason and Wiik, 1960a
Tommhannock Creek Cb	26.31	26.10	Mason and Wiik, 1960b
Tromöy Cb	26.32	25.58	Wiik, 1956
Collescipoli Cb	26.88	26.03	Wahl, 1950b
Oakley Cb	26.96	26.32	Wahl, 1950a
Miller Cb	27.01	25.56	Mason and Wiik, 1961b
Hainaut Cb	27.02	26.53	Wiik, 1956
Estacado Cb	27.88	27.73	Mason and Wiik, 1963
Ochansk	27.91	27.16	Wiik, 1956
Richardton Cb	29.79	29.41	Mason and Wiik, 1963
Atlanta Ce	28.95	28.67	Wiik, unpublished
St. Marks Ce	32.43	32.72	Wiik, unpublished
Indarch Ce	33.15	34.04	Wiik, 1956
Rose City Cb	36.40	36.20	Wiik, unpublished
Steinbach S	52.98	54.36	Winkler, 1879

TABLE 2—(*Continued*)

	Weight Per Cent of Fe	Cation Per Cent of Fe	References
Marjalahti P	75.80	74.23	Borgström, 1903
Alais Cc Type I	17.76	27.00	Mason, 1963
Orgueil Cc Type I	18.42	27.34	Wiik, 1956
Cold Bokkeveld Cc Type II	20.85	26.28	Wiik, 1956
Erakot Cc Type II	22.42	27.67	Mason and Wiik, 1962
Norton County Ae	1.60	1.43	Wiik, 1956
TEKTITES			
Caramut, Victoria	3.96	4.13	Taylor, 1962
Talangatuk, Victoria	3.47	3.62	Taylor, 1962
Kalgoorlie, Western Australia	3.99	4.11	Taylor, 1962
Charlotte Waters, central Australia	3.47	3.66	Taylor, 1962
IGNEOUS ROCKS			
Granite, Rhode Island (G-1)	1.42	1.43	Fairbairn, 1953
Diabase, Virginia (W-1)	7.81	7.88	Fairbairn, 1953

It cannot be by chance that, with these different components, the sum in so many cases is close to 1.79. For a meteorite consisting of pure enstatite, $MgSiO_3$, the sum will be 2.00, and for a meteorite consisting of pure ferrosilite, $FeSiO_3$, the sum will be 1.50. Tatahouine, a hypersthene achondrite, consists of pyroxene of $MgSiO_3$ and $FeSiO_3$ in proportions to give a sum of 1.85. Thus $2.00 - 1.79 = 0.21$ and $1.79 - 1.50 = 0.29$, but Tatahouine gives $1.85 - 1.79 = 0.06$, yet it is one of the meteorites that satisfies the equation least well. Meteorites consisting of pure $FeSiO_3$ are unknown, but meteorites consisting of nearly pure $MgSiO_3$ do occur. The latter give a sum near 2.00 and thus do not obey the iron equation. On the other hand an enstatite chondrite, for example, Atlanta, which consists of about 7 per cent of FeS, 26 per cent of nickel-iron, and the rest almost pure $MgSiO_3$, gives a sum of 1.80. One may consider this in terms of Ringwood's proposal (1961):

Enstatite achondrites plus iron meteorites equals enstatite chondrites; hence enstatite achondrites are meteorites of secondary derivation. It should be noted that the nickel-iron in the enstatite chondrites has approximately the same composition as that of the commonest of the iron meteorites. Thus, together the meteorites poorest in iron and those richest in iron form a unit which obeys the iron equation. Carbonaceous chondrites of types I and II do not satisfy the equation; they contain excessive

amounts of "volatile" elements—O, H, C, and S. If these excessive amounts are removed, we have the carbonaceous chondrites of type III, the olivine-pigeonite chondrites. On a volatile-free basis the three types have essentially the same composition, and they all belong to the H (high-iron) group of Urey and Craig (1953). Since the olivine-pigeonite chondrites and the olivine-bronzite chondrites satisfy the equation, one might expect some possibility of applying the equation to the carbonaceous chondrites. How such application should be made is not yet clear.

The fact that the iron equation is valid also for tektites may indicate that these are some form of meteorite. The fact that plutonic rocks agree so well with the equation leads one to the hypothesis that these rocks consist of rather undifferentiated material from the original formation of the earth.

Iron thus plays a decisive role in meteorites. Meteorites can be considered as consisting of iron plus other material that can potentially form iron or have been iron. Take, for example, the Rose City meteorite. It contains 36.4 per cent of iron, which also amounts to 36.2 cation per cent of iron. Thus in a sample of Rose City containing 36 iron atoms, these atoms make up 36 per cent of the total mass of the sample, and all the remaining material has a weight corresponding to 64 iron atoms; the whole sample thus has a mass corresponding to 100 iron atoms. The nickel and cobalt contents can be added to that of iron without affecting the calculations. However, for convenience we consider the iron alone.

It is tempting to explain the formation of meteorites by assuming a splitting up of a substance, originally consisting mostly of iron, partly into lighter atoms. Such a split would happen in a closed system, but from time to time the source in which these reactions took place (for example, a nova) would throw out into space the meteorite-forming material. The meteoritic material would hence be of the second-generation type. The iron-nickel would be the first. There are some astronomical evidences for such a sequence of events (Bowen, 1964; Fowler, 1964).

It is seen from analyses that the elements preceding the iron group diminish disproportionately quickly with increasing iron content. See table 3, in which the elemental weight percentages in the three chondrite groups (L, H, and HH) are given: this table includes my own analyses plus those of the stony irons (Steinbach and Marjalahti). Since 1956 when I suggested that a group of chondrites existed richer in iron than Urey and Craig's H group, which I called an HH group, two more examples have been found (Rose City and St. Marks). This HH group cannot be converted into the H group by oxidation or reduction, just as the H and L groups cannot be transformed one into the other by these processes.

TABLE 3
CHEMICAL COMPOSITION OF METEORITES OF THE L, H, AND HH
GROUPS IN WEIGHT PERCENTAGES OF THE ELEMENTS
(The number of analyses is given in parentheses.)

	Fe	Ni	Co	Ti	Mn	Cr	Mg	Si	Ca	S
L (17)	21.15	1.10	0.05	0.08	0.25	0.38	15.03	18.74	1.21	2.28
H (29)	24.89	1.42	0.07	0.07	0.19	0.31	13.33	15.34	1.31	2.46
HH (3)	33.97	1.96	0.10	0.06	0.21	0.31	11.34	15.88	0.97	4.90
Steinbach S	53.01	4.95	0.12	—	0.12	0.15	5.09	12.83	0.70	2.63
Marjalahti P	75.80	6.60	0.34	0.01	0.06	0.08	5.68	3.77	0.00	—

Continuing analytical work since 1956 has further confirmed the validity of the H and L groups. It has also been shown that the L group, instead of having a uniform degree of oxidation (Wiik, 1956), has a somewhat variable one (Wood, 1963, p. 352; Mason, 1962a). The amphoterites, which show a range of oxidation, have proved to be highly oxidized L-group chondrites (Mason and Wiik, 1964).

The figures in table 3 are influenced by the considerable variation in the degree of oxidation within each group; as a result the weight percentages within each group vary considerably from one meteorite to another. A better perception of the differences between the three groups can be obtained from some recent analyses (table 4).

Tables 3 and 4 show the tendency for certain elements to increase and others to decrease in a non-uniform way. Urey and Craig, in their 1953 paper, remarked that the Fe/Ni ratio was not the same in the H and L groups. With increasing iron content, the nickel content increases disproportionately. According to Urey and Craig the Fe/Ni ratio is 21.07 in the L group and 17.01 in the H group. We see from table 3 that this tendency continues in the HH group and in the stony irons. It seems clear therefore that these different groups cannot be related to one another through chemical reactions. Oxidation or reduction will not affect, for example, the Fe/Ni ratio. The tendency for certain nuclides to increase or decrease disproportionately with increasing iron content becomes still clearer if we go beyond nickel in the periodic system. Table 5 gives some determinations of the platinum metals and gold in one chondrite of the H group and two of the L group. A 50-gram sample of each meteorite was taken, and the platinum metals and gold were concentrated and extracted by cupellation. The small Pt-Au button was dissolved in aqua regia and absorbed together with a molybdenum internal standard in a carbon electrode, which was fired in a Jarrell-Ash grating spectrograph.

TABLE 4

CHEMICAL COMPOSITION OF THE L, H, AND HH GROUPS OF METEORITES

(Analyses of two subgroups of different degrees of oxidation are given for each group.)

	Fe	Ni	Co	Mn	Mg	Si	Ca	S	(O)
L									
Vårvik (Näs) Ch (amphoterite)	21.30	0.99	0.06	0.27	15.83	19.43	1.15	2.32	38.5
Holbrook Ch	21.56	1.09	0.05	0.29	15.18	18.74	1.24	2.90	36.5
H									
Estacado Cb	27.88	1.46	0.09	0.22	13.51	16.73	1.07	2.07	34.0
Atlanta Ce	28.95	1.68	0.12	0.12	12.96	17.72	0.27	2.62	32.5
HH									
St. Marks Ce	32.43	1.81	0.10	0.28	11.63	17.13	0.87	5.50	28.9
Rose City Cb	36.40	2.24	0.13	0.17	11.92	14.04	0.86	3.52	27.9

The results show that Forest City, an H-group chondrite, has twice as much platinum metals and gold as the L-group chondrites. Even if the figures are not absolute values, the proportions are reliable. Hara and Sandell (1960) found 10 times more ruthenium in chondrites than is given in table 5. However, their proportions for this element between L and H groups are similar to mine. Thus the L and H groups differ from each other not only in Fe content but also in the amounts of many other elements. For some of these (e.g., Ni or Pt) the relative differences are much greater than the difference for Fe.

It is thus clear that the L, H, and HH groups cannot be changed into one another by chemical reactions. I would go a step further and postulate that even within a single group the subgroups cannot be interconverted by reactions that involve oxidation or reduction; such a pos-

TABLE 5

OPTIC SPECTROGRAPHIC DETERMINATIONS (IN PARTS PER MILLION)
OF PLATINUM METALS AND GOLD IN THREE CHONDRITES

	Holbrook Ch L (Mason and Wiik, 1961b)	Bjurböle Ch L (Unpublished)	Forest City Cb H (Unpublished)
Ru	0.06	0.06	0.14
Rh	0.064	0.064	0.140
Pd	0.44	0.44	0.76
Os	0.16	0.14	0.16
Ir	0.24	0.26	0.44
Pt	0.44	0.42	0.98
Au	0.04?	0.16	0.28

tulate can be deduced from table 4. It is not obvious in the case of the L group; the iron contents of Vårvik and Holbrook are quite similar. However, in the H group the trend is clear. From Estacado (Cb) to Atlanta (Ce) the nickel and cobalt contents increase disproportionately to the iron content, whereas the manganese content decreases disproportionately. The same trend is also seen in the HH group. There is evidently some genetical connection between the groups and between the subgroups within the individual groups. A consistent relationship exists from one group to another. The increase in Fe content can be taken as a guide line in the development of the whole system. However, this development cannot proceed through chemical reactions. It must involve nuclear reactions. On the basis of the iron equation (tables 1 and 2) and the consistent changes in chemical composition from group to group (tables 3, 4, and 5), I suggest that meteorites are products of nuclear reactions and that each meteorite group (and subgroup) represents an equilibrium product of these reactions. That nothing has been added and nothing removed is shown by the stoichiometric regularities. The probability is small that after gravitational differentiation the iron equation should be satisfied or that the groups would have constant composition. For the same reasons it is most improbable that meteorites are random agglomerates after collisions between extraterrestrial bodies. I agree with Mason (1960), who wrote, "The chondritic meteorites . . . have always been independent and individual objects . . . showing no sign of gravitational segregation." However, I would not limit this statement to the chondrites, but extend it to all meteorite groups. The constant composition of the individual groups is highly significant. For example, the olivine-hypersthene chondrites of the Holbrook class [or, as Prior (1920) called them, the Baroti class] have a constant composition which extends even to the minute amounts of the rare earth elements (Schmitt, Smith, and Olehy, 1964) and the platinum group of elements, as shown above. Of the stony meteorites that I have analyzed, 10 belong to this homogeneous Holbrook class. Such homogeneous "rocks" cannot have been formed by chemical or mechanical differentiation. The constant composition of specific meteorite groups is more reminiscent of chemical compounds than of mechanical mixtures. We are dealing with mechanical mixtures of minerals, with the minerals sometimes varying in composition within a single meteorite (Keil and Fredriksson, 1963), in which the bulk composition is constant.

The principal meteorite groups apparently represent widely different equilibria within a closed system; the subgroups, small variations in equilibrium. If this theory is valid, then there should be consistent mathe-

matical relationships between, for example, the Fe content in different groups if all groups are derived from a common source and the reactions occurred in a closed system. Nuclear reactions presumably follow mass-action laws similar to those for chemical reactions, and we can therefore expect logarithmic curves for the amounts of the different elements.

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